A Cautionary Tale about Volatile-Rich Carbonaceous Chondrites

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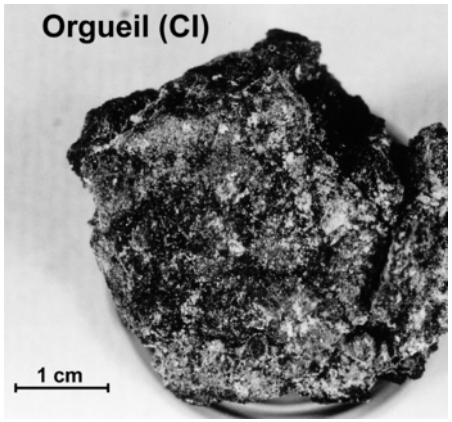
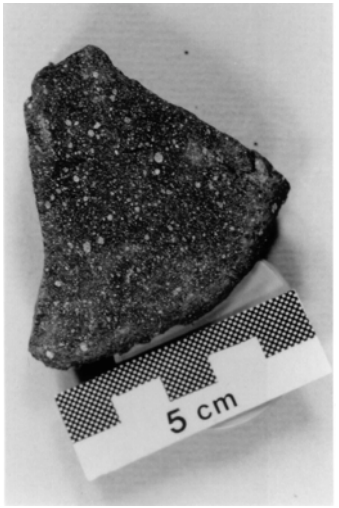




Why Care about Carbonaceous Chondrites?

	EH	EL	H	L	LL	R	CK	CV	CO	CH	CR	CM	CI
Physical properties													
Chondrule diam.	0.2–0.6	0.8	0.3	0.7	0.9	0.4	0.7	1	0.2–0.3	<0.1	0.8	0.3	–
Metal grain size	–	–	0.2	0.18	0.14	–	–	–	–	6	–	–	–
Chondrule abund.	20–40	20–40	65–75	65–75	65–75	≥40	15	35–45	35–40	~70	52	~15	0
Metal abund.	22	18	16	6	2	0.1	<0.01	0–7	0–5	20	6.3	0	0
Matrix abund.	<5	<5	10–15	10–15	10–15	35	75	40–50	30–40	5	44	~60	100
Compositional properties													
Carbon	0.42	0.32	0.11	0.12	0.22	–	0.1	0.43	0.38	–	1.97	1.82	2.8
Water	1.9	1.6	0.22	0.46	0.71	–	1.6	0.25	3.3	–	7.11	10.4	16.9
Fe_m/Fe_t	0.76	0.83	0.58	0.29	0.11	~0	~0	0–0.3	0–0.2	0.95	0.22	0	0
Fe/Si	0.95	0.62	0.81	0.57	0.52	–	0.83	0.76	0.77	2.2	0.81	0.8	0.86
Mg/Si	0.77	0.83	0.96	0.93	0.94	–	1.13	1.07	1.05	1.02	1.06	1.05	1.05
Ca/Si	0.035	0.038	0.05	0.046	0.049	–	0.068	0.084	0.067	0.017	0.06	0.068	0.064
$\delta^{17}O$	3	2.7	2.9	3.5	3.9	5.27	−5	~−4.0	~−5.1	~−1.3	~−0.7	~4.0	~8.8
$\delta^{18}O$	5.6	5.3	4.1	4.6	4.9	4.74	−1	~0	~−1.1	~0	~2	~12.2	~16.4

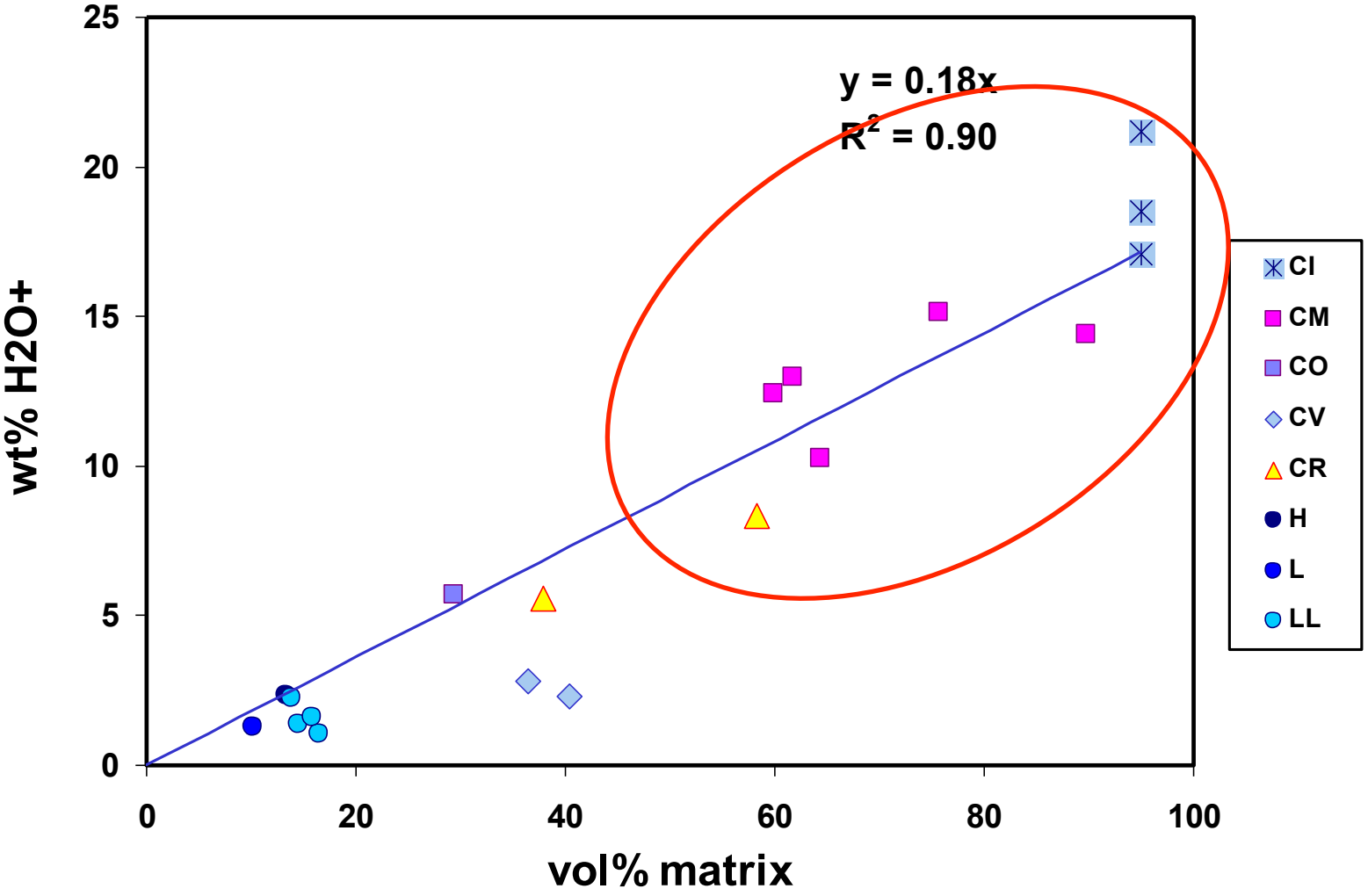
Units: chondrule diameter and metal grain size, mm; chondrule and matrix abundance, vol. %; metal, carbon, and water abundance, wt %; Fe_m/Fe_t, Fe/Si, Mg/Si, and Ca/Si, atom ratio; $\delta^{17}O$ and $\delta^{18}O$, per mil.

References: Wiik (1969), Sears and Axon (1975; 1976), Dodd (1976), Afiattalab and Wasson (1980), Grossman *et al.* (1988b), Scott (1988), Sears and Dodd (1988), Weisberg *et al.* (1988b; 1991; 1993), Jarosewich (1990), Kallemeyn *et al.* (1991; 1996), Zhang *et al.* (1995), Scott *et al.* (1996), Krot *et al.* (2002).

Volatile-Rich Carbonaceous Chondrites

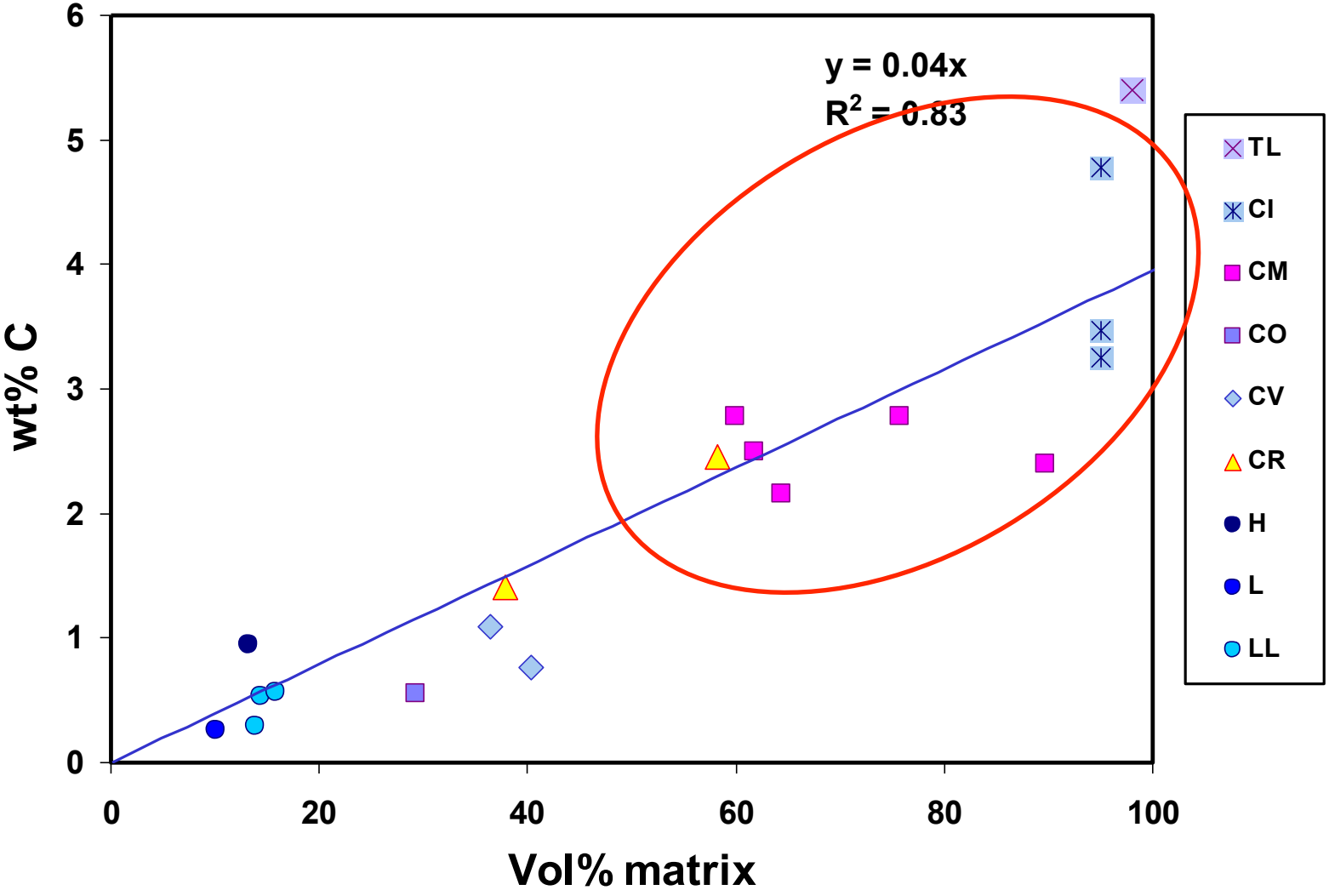
- Sources of water, OH, and organics
- Largely composed of low-temperature components
- Typically highly porous
- Typically are weakly bound aggregates. Low compressive strength
- High potential for ISRU

The Volatiles are in the Matrix



Petrographic types ≤3.4 (after Bonal et al. for CCs)

The Carbon is in the Matrix



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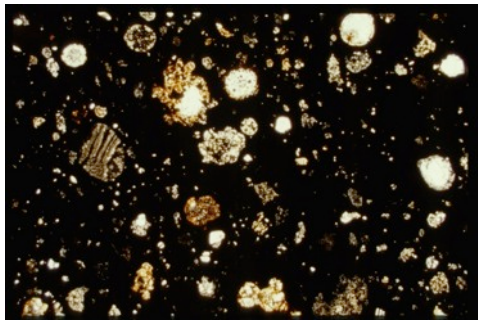
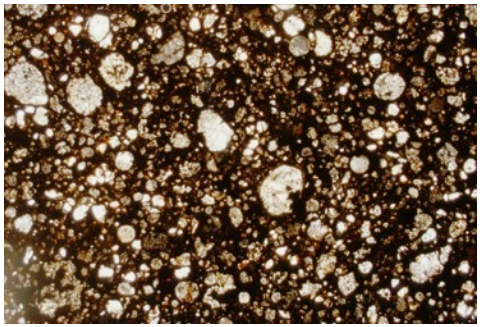
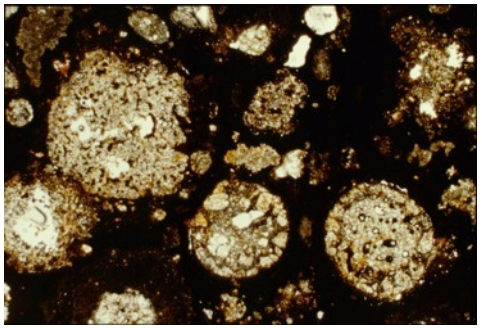
What is Matrix?





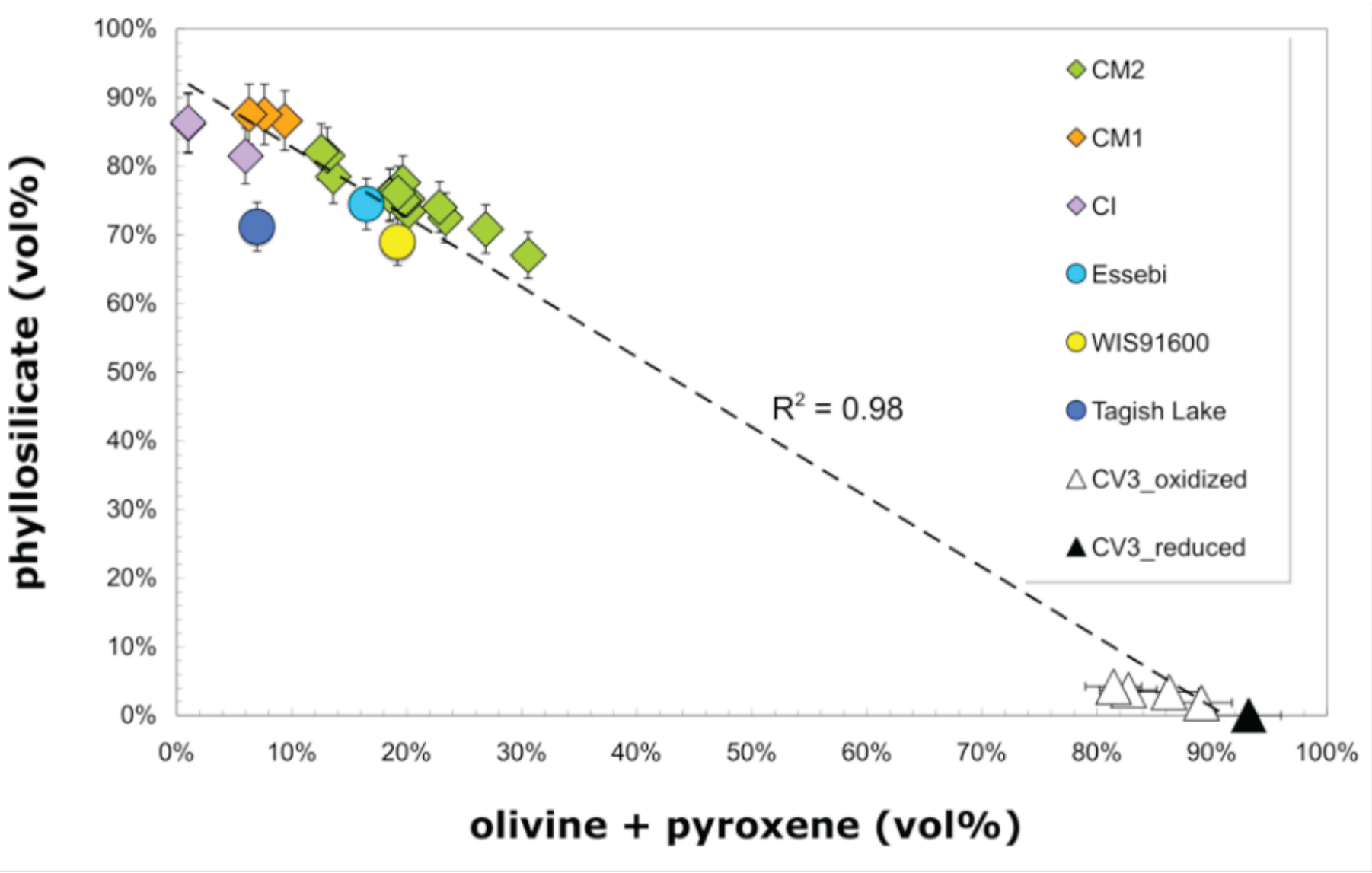


	% matrix
CI	>99
CM	70
CO	34
CV	40

Very fine-grained material

- In physical and chemical disequilibrium (Mg#, crystals and amorphous grains…)
- Rich in volatile elements, water, OH, clays
- Containing presolar grains and primitive organic compounds
- Low-temperature materials

The Silicates Tend to be Clays



Looking at terrestrial analogs

- Mineralogy of a Tagish Lake analog
- Hydrated phyllosilicate minerals, silicates, oxides, sulfides, carbon compounds (mostly kerogens),…… pretty straightforward mineralogy
- Except for the kerogens

(Image courtesy of Mike Zolensky, NASA JSC)

Mineral
Serpentine
Kerogen
Magnetite
Pyrrhotite
Olivine

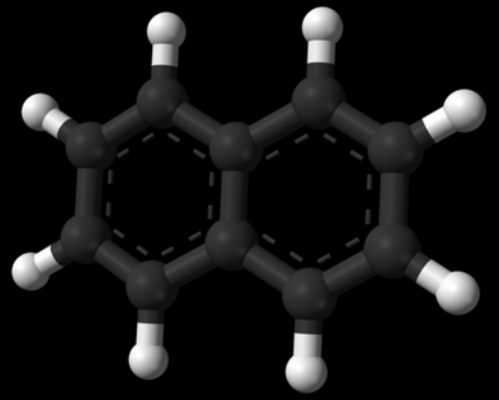
Meteoritic Kerogens

- Rich in Polycyclic Aromatic Hydrocarbons (PAHs)
  - Aromatic: Term was coined as such simply because many of the compounds have a sweet or pleasant odor
- More than 20% of the carbon in the universe may be associated with PAHs.
- "PAHs form when complex organics are exposed to high temperatures or pressures."
  - Like regolith processes
- PAHs have more carbon atoms than hydrogen.
  - For example: Naphthalene $C_{10}H_8$
- Source of carbon (to make methane) and hydrogen (make water)
- We do need to be a bit careful with PAHs

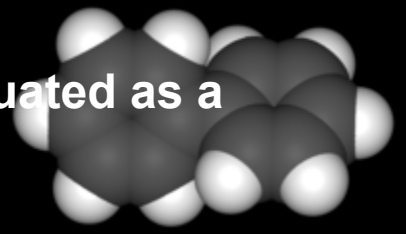
Types of Kerogen and Their Hydrocarbon Potential

Environment	Kerogen Type	Kerogen Form	Origin	HC Potential
Aquatic	I	Alginite	Algal bodies	
		Amorphous Kerogen	Structureless debris of algal origin	Oil
			Structureless planktonic material, primairly of marine origin	
Terrestrial	II			
		Exinite	Skins of spores and pollen, cuticle of leaves and herbaceous plants	
	III	Vitrinite	Fibrous and woody plant fragments and structureless, colloidal humic matter	Gas, some oil
				Mainly gas
	IV	Inertinite	Oxidized, recycled woody debris	None

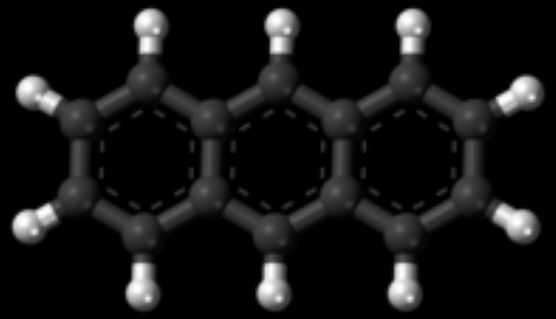
Some PAHs



- Naphthalene $C_{10}H_8$
  - The active ingredient of moth balls.
  - With inhalation exposure it affects red blood cells creating all the symptoms of hemolytic anemia.
  - If the inherited condition of glucose 6-phosphate dehydrogenase deficiency is present it causes hemolytic anemia at very low doses.
  - In the USA permissible limits decreasing. Banned in European Union. Partially banned in California.
- Biphenyls $(C_6H_5)_2$
  - Starting material for the production of polychlorinated biphenyls (PCBs)
  - Mildly toxic, used as preservative in foods, emulsifier in combination with other food additives. No longer used in some countries.
  - National Institute of Safety and Health has it reevaluated as a toxicant.
  - Completely banned in California.

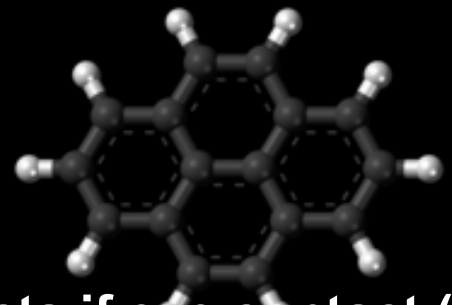


Some PAHs



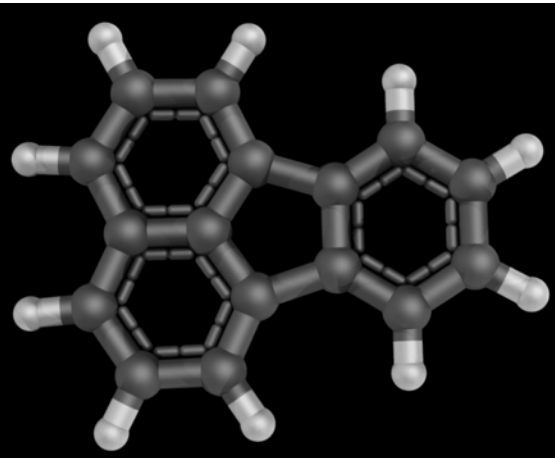
- Anthracene $C_{14}H_{10}$
  - Toxicant, classified as dangerous substance with strict regulations, and decreasing exposure limits.
  - Potential acute health effects are; very hazardous in case of skin contact (irritant and sensitizer), eye contact (irritant), and inhalation. Hazardous in case of skin contact (permeator), or ingestion.
  - Mutagenic, teratogenic, developmental toxicology are not available.
  - It is known that this substance is toxic to the kidneys, lungs, mucous membranes.
  - Repeated or prolonged exposure can cause severe damage to organs.
  - Inhalation of dust may lead to chronic respiratory disease.

Some PAHs



- Pyrene $C_{16}H_{10}$
  - Toxicant with potential acute health effects if eye contact (as irritant), ingested, or inhaled.
  - Slightly hazardous if skin contact but with rapid skin absorption.
  - Target organs are liver, blood, and kidney.
  - Potential chronic health effects are carcinogenic, mutagenic to mammalians specifically to somatic cells (non-reproductive cells) but teratogenic or developmental toxicity is not available.
  - High toxicity to animals with acute oral toxicity and also highly mutagenic in animals. The effects on humans are not well studied.
  - Possible that long term biodegradation products will create exponential effects on toxicity.

More PAHs



- Fluoranthene $C_{16}H_{10}$
  - Potential acute health effects are hazardous in case of ingestion.
  - However potential chronic health effects including carcinogenic, mutagenic, teratogenic and developmental toxicity are suspected but unknown.
  - There are some known chemical properties such as risk of explosion in the presence of mechanical impact but there is no data available on flash point, flammable limits, LD50, LC50 and other toxicological data in humans.
  - EPA has it classified as high priority as pollutant, highly carcinogenic to most animals.

Some Thoughts about PAHs

- These are combustion residues….your barbeque grill is probably far more toxic than any meteorite.
- However, the toxicity risk of PAHs in carbonaceous chondrites needs to be studied.
- Toxicity of PAHs will need to be factored into plans:
  - Design of ISRU extraction hardware.
  - Robotic and Human operations on asteroids.
  - Experimental design of any testing and processing using meteoritic material.
  - Development of engineering and chemical analogs for asteroidal material.